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Thermodynamic analysis of a gas turbine cycle equipped with a non-ideal adiabatic model for a double acting Stirling engine

Mahmood Korlu [a], Jamasb Pirkandi [a,*], Arman Maroufi [b]

[a] Department of Aerospace Engineering, Malek Ashtar University of Technology, Tehran, Iran
[b] Faculty of Industrial and Mechanical Engineering, Islamic Azad University, Qazvin Branch, Qazvin, Iran

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ABSTRACT

The aim of this study is to investigate the thermodynamic performance of a gas turbine cycle equipped with a double acting Stirling engine. A portion of gas turbine exhaust gases are allocated to providing the heat required for the Stirling engine. Employing this hybrid cycle improves gas turbine performance and power generation. The double acting Stirling engine is used in this study and the non-ideal adiabatic model is used to numerical solution. The regenerator's net enthalpy loss, the regenerator's wall heat leakage, the energy dissipation caused by pressure drops in heat exchangers and regenerator are the losses that were taken into account for the Stirling engine. The hybrid cycle, gas turbine governing equations and Stirling engine analyses are carried out using the Matlab software. The pressure ratio of the compressor, the inlet temperature of turbine, the porosity, length and diameter of the regenerator were chosen as essential parameters in this article. Also the hybrid cycle effects, efficiency and power outputs are investigated. The results show that the hybrid gas turbine and Stirling engine improves the efficiency from 23.6 to 38.8%.

1. Introduction

Finding new energy sources seems to be inevitable because the ever increasing worldwide energy demand, the limited fossil fuel resources, and the environmental pollution. Gas turbine is one of the energy sources with many applications in various industry such as aerospace, auxiliary power units in airplanes, industrial projects, transport industry and cogeneration systems. Every gas turbine consists of a compressor, combustion chamber where air and fuel are mixed and burned and a turbine that converts the hot and compressed gases energy into mechanical energy. A portion of the mechanical energy produced by the turbine is consumed to rotate the compressor and the rest of it is transported to the generator to produce electricity. Gas turbine's works based on the Brayton cycle. The cycle was first proposed by John Barber [1], an English inventor. The researches of the recent 7 decades have increased the gas turbine efficiency. Also researchers try to find new methods to improve the efficiency without an overhaul. One way to improve the gas turbine efficiency achieved by changing operational conditions (temperature and pressure) and various cooling methods, the other way is to combine the gas turbine with another thermal engine, which can significantly improve power and efficiency. Combing the gas turbine with the Rankine and the Stirling cycles is an effective way of increasing efficiency.

The gas turbine cycle and the Stirling cycle combination results a wholly different configuration. In this type of hybrid cycle, exhaust gases enter Stirling engine heat exchanger and provide the heat required by the Stirling engine [2]. In 2005, Pollikas estimated, for the first time, that using a bottoming Stirling cycle fed by exhaust gases of an RB211 Rolls-Royce gas turbine (27.5 MW electrical power) can recover 9 MWs. Adding a Stirling engine to a gas turbine can make a 47.7% overall efficiency[3].

Many researchers interested in Stirling engines due to low pollutant emissions, low sound production and the ability to operate with various fuels [4–6]. In fact, a Stirling engine is an external combustion engine and can use any external heat source and convert it into mechanical energy. The studies carried out by researchers on Stirling engine design and applications have produced very promising results. Construction of a solar engine with a 10 kW axial power is one of the most significant advances in Stirling technology. Combined heat and power generation is one of the new ideas that have been developed by Stirling manufacturers and are used in power plants. Recently, there are new ideas for the Stirling engine applications such as satellite power supply and being proposed as an alternative to steam turbines in nuclear power plants. Stirling engines' physical structure consists of five

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* Corresponding author.
E-mail address: j_pirkandi@dena.kntu.ac.ir (J. Pirkandi).

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Nomenclature

A	area [m^2]
C_p	specific heat at constant pressure [J/kg K]
C_v	specific heat at constant volume [J/kg K]
d	hydraulic diameter [m]
f	friction factor coefficient
g	mass flux [kg/m^2 s]
$\bar{h}$	enthalpy [kJ/kmol]
k	thermal conductivity [W/m K]
l	length [m]
LHV	lower heating value [kJ/mol]
m	mass [kg]
M	mass of working gas in the Stirling engine [kg]
$\dot{n}$	molar flow rate [mol/s]
NTU	number of transfer units
P	pressure [bar]
Pr	non-dimensional Prandtl number
$\dot{Q}$	heat transfer rate [kW]
Q	heat [kJ]
R	universal gas constant [8.314 J/kmol K]
Re	non-dimensional Reynolds number
r_p	compressor pressure ratio
St	non-dimensional Stanton number
T	temperature [K]
TIT	turbine inlet temperature [K]
V	volume [m^3]
$\dot{W}$	power [kW]
W	work [kJ]

Greek symbols

ρ	density [kg/m^3]
η	efficiency
θ	crank rotational angle [°]
γ	ideal gas specific heat ratio
ε	heat exchangers and regenerator effectiveness
μ	viscosity [kg/m s]

Subscripts

a	actual process
a.c	air compressor
c	compression space
cc	combustion chamber
ck	interface between compression space and cooler
clc	compression clearance volume
cle	expansion clearance volume
diss	dissipation
e	expansion space
elec	electrical
f.c	fuel compressor
gen	generator
gt	gas turbine
g	gas
h	heater
he	interface between heater and expansion space
k	cooler
kr	interface between cooler and regenerator
loss	loss
r	regenerator
rh	interface between regenerator and heater
rloss	net enthalpy loss
s	isentropic process
suth	Sutherland
st	Stirling engine
swc	compression swept
swe	expansion swept
w	wall
wg	wetted area
wh	heater wall
wk	cooler wall
wr	regenerator wall
wrloss	losses from the regenerator walls

subsystems, and each the subsystem is considered a control volume. The engine consists of two spaces with varying volumes, named expansion space and compression space, and three heat exchangers with constant volume, named heater, cooler and regenerator.

Many researchers study the Stirling engine ever since its invention by Robert Stirling. The first acceptable mathematical analysis of the Stirling cycle was developed by Schmidt, fifty years after its invention [7]. Schmidt's analysis was based on isotherm expansion and compression spaces, in his approach the thermodynamic models were linearized and therefore, the initial power and engine efficiency calculations were fairly simple. Finkelstein [8] improved Schmidt's thermodynamic analysis and proposed the first adiabatic analyses. Urieli and Berchowitz [9] used the thermodynamic model to calculate power output and efficiency of Stirling engines. Fermosa and Despesse [10] modelled the engine using an isotherm model to investigate dead spaces' effects on the engine power output and efficiency. Popescu et al. [11] shows that the low performance is essentially caused by the non-ideal thermal regenerator. Kaushik, Cun-quan and Wu [12–14] proved that thermal regenerator effectiveness factor, thermal conductivity between engine and reservoir have the highest impacts on Stirling engines performance. Kongtragool and Wongwises [15] studied the effects of regenerator effectiveness and dead spaces on Stirling engine inlet heat and efficiency. Costa et al. [16] and Timoumi et al. [17–20]investigated Stirling engine losses and irreversibilities through adiabatic modeling. Thombare and Verma [4] have conducted a series of studies in which they gathered the available technologies and recent advances in Stirling engine analyzation and provided some suggestions as how to use them. Tavvakolpour et al. [21] investigated the gamma type Stirling engine, they used the Schmidt theory to solve the equations in isotherm form and used flat panel to absorb solar energy as the hot thermal source. Gostante and Invernizzi [22] modelled the Stirling engine and then investigated the effects of various gases on the engine output and efficiency. In the present study, the energy of a gas turbine exhaust gases are used as the hot source in a double acting Stirling engine. The thermodynamic equations of every single component of the gas turbine and double acting Stirling engine hybrid cycle are simulated by a code written in Matlab. The non-ideal adiabatic model is used to model the Stirling engine. Then, with parametric study for the mentioned hybrid system, the effect of gas turbine inlet temperature, compressor pressure ratio, regenerator porosity and regenerator length and diameter on gas turbine, Stirling engine and hybrid cycle performance are investiagated.

2. System configuration

A schematic of the proposed hybrid system can be seen in Fig. 1. As can be seen, the hot exhaust gases enter a heat exchanger where it heats up Stirling engine working fluid. This method can prevent exhaust gases' thermal losses since some of the heat will be used in the Stirling engine and electric power generation. In the proposed